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TITLE: GEOMETRY, CONTACT, SURFACE, AND OPTICAL DEVELOPMENTS FOR PHOTOCONDUCTIVE POWER SWITCHES

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FOR
PHOTOCONDUCTIVE POWER SWITCHES*

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Introduction

Photoconductive Power Switches (PCPSs) have the advantages of precise control, extremely fast closure times, extremely low inductances, and scalability to very high voltages and currents[1,2]. PCPSs have these advantages because the size or power of the switch is not related to its closure time. The closure time is determined by the external optical source that uniformly illuminates the PCPS between the electrodes. Because carriers are generated uniformly between the electrodes at the desired density, current can flow through the switch immediately without waiting for carrier transit delays. The operating voltage is determined by the switch length ℓ, and the operating current is determined by the switch width w, as illustrated in Figure 1. The electrodes can be made as wide as desired so that the inductance can be extremely low, or the area available for heat removal can be increased and the entire switch brought into conduction at the same instant if the same optical pulse and path length are used. This paper describes recent research at Los Alamos[2] that has improved PCPS contact fabrication technology, has developed a simple optical control illumination system using fiber optics and rectangular optics, and has improved photoconductor surface fabrication methods and processes for high electric field operation.

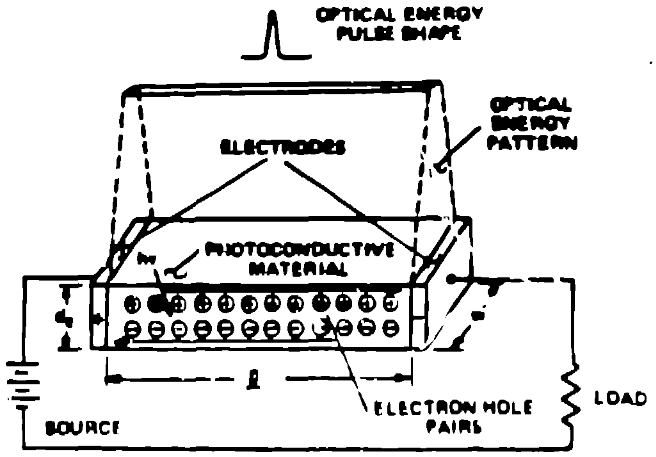

Figure 1. Basic PCPS geometry.

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Current Density Limitations

The physical effects limiting the practical carrier density in a silicon photoconductor include Auger recombination, free-carrier photon absorption, mobility reduction due to carrier-carrier scattering, and local thermal runaway due to the variation of mobility with temperature[2]. The above considerations limit the maximum practical carrier density to about 10^{18} cm^{-3} (Ref. 3). This carrier density limits the allowable current density and, when coupled with the photoconductor optical absorption depth, limits the photoconductor current capability per unit width.

The optical absorption depth for GaAs and silicon versus wavelength is shown in Figure 2. In addition, the vertical line at 1.09 µm corresponds to the bandgap energy of silicon or the lowest energy photon that can be used to produce an electron-hole pair in silicon. The vertical line in Figure 2 at 0.89 µm corresponds to the lowest energy photon that can be used with GaAs.

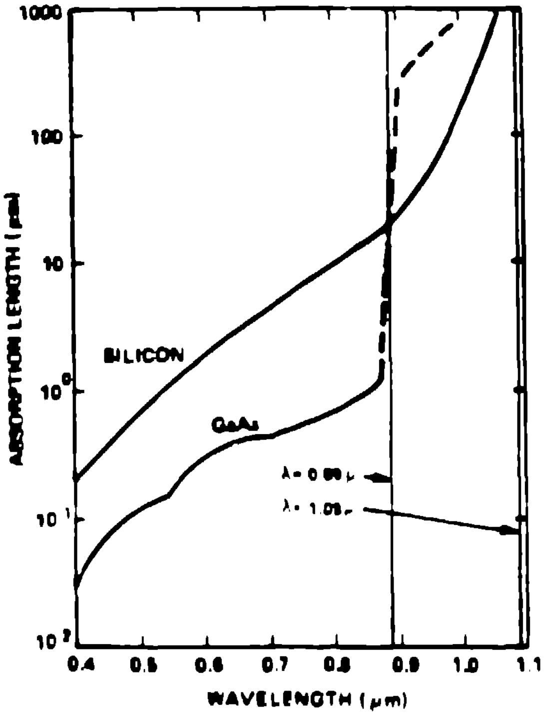


Figure 2. Optical absorption depth for silicon and GaAs.

The maximum practical current density J_{max} is dependent on the maximum practical carrier density[3]:

$$J_{max} = n_{p-max}\, e\, v_c = n_{p-max}\, e\, \mu\, E_c \quad , \qquad (1)$$

where n_{p-max} is the maximum pair carrier density, e is the electron charge, μ is the sum of the electron and hole mobilities, v_d is the drift velocity, and E_c is the conduction electric field. For intrinsic silicon with $\mu = 0.05\ m^2/V\text{-}s$ at a carrier density of $10^{24}\ m^{-3}$, $E_c = 10^5$ V/m, $n_{p-max} = 10^{24}\ m^{-3}$, and $J_{max} = 50 \times 10^3\ A/cm^2$. The current density is related to the current per unit width by the optical absorption depth d_e (Ref. 3), or

$$I_w = J_{max}\, d_e = n_{p-max}\, e\, \mu\, E_c\, d_e \quad , \qquad (2)$$

which for silicon, using $d_e = 1$ mm, is about 5 kA/cm. If we assume that the optimum carrier density for GaAs is similar to that for silicon and use $0.4\ m^2/V\text{-}s$ as the mobility of GaAs with a similar conduction electric field, GaAs can conduct only 800 A/cm of width. Thus, the absorption depth plays a very important role in photoconductive power switching.

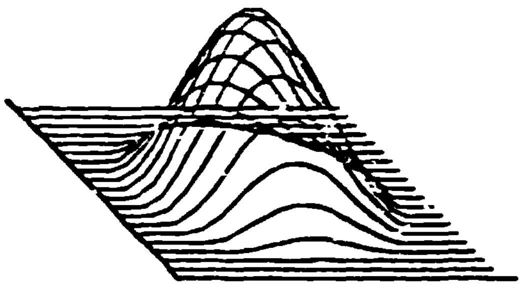
Uniform Optical Energy Density and Illumination

In order to limit the carrier density in the photoconductor to n_{p-max}, the optical energy incident on the surface must be limited. The optical energy density E_{Ld} on the photoconductor is related to the number of hole-electron pairs n_p (Ref. 3) produced by

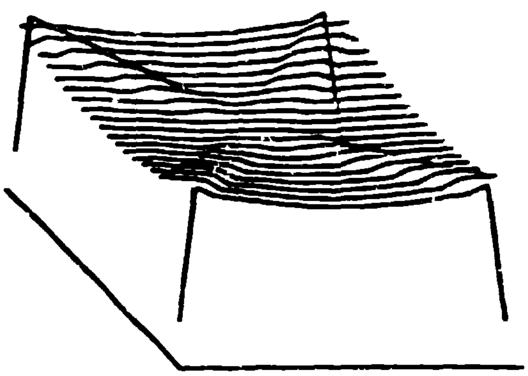
$$E_{Ld} = n_p\, E_\lambda\, d_e/(1 - r) \quad , \qquad (3)$$

where E_λ is the photon energy and r is the surface reflection coefficient. For silicon, the optical energy on the surface should be limited to about 10 mJ/cm^2 to limit the carrier density to $10^{18}/cm^{-3}$. Note that the competing processes mentioned earlier such as Auger recombination and free-carrier absorption will tend to limit the carrier density to $10^{18}/cm^{-3}$ in an equilibrium situation.

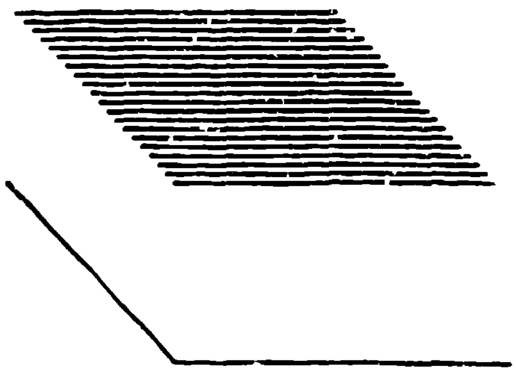
The simple method of uniformly illuminating a PCPS was developed using fiber optics and rectangular optical components[3]. The use of cylindrical lens pairs is very inefficient because only a small area of the optical pattern has a relatively uniform intensity distribution[3]. Simple illumination with multiple optical fibers with Gaussian intensity distributions generates a large intensity variation along the switch[3]. In order to deliver an equal amount of energy to each optical fiber, the source intensity must be homogenized across its aperture. In addition, the optical energy arriving at the switch must be homogenized from the somewhat Gaussian intensity distribution leaving the fiber to the square or rectangular distribution required for the switch area associated with each fiber. These two requirements can be satisfied by the phase mixing that occurs during propagation of a Gaussian optical pulse along an optical path with a square cross section[4-6]. The transformation of a Gaussian distribution into a square distribution is illustrated by the calculated intensity profiles of Figure 3 (Ref. 5). This principle is used to illuminate the cylindrical PCPSs with the rectangular acrylic homogenizer as shown in Figure 4 and to illuminate a low-inductance-strip PCPS with the rectangular homogenizer as shown in Figure 5. The measured intensity distribution at the output of the homogenizer using a photodiode array with a diode spacing of about 50 μm is



(a) Calculated intensity distribution after traversing 2-mm length of 1-mm square fiber from axial point source with cosine-squared NA of 0.25.



(b) Calculated intensity distribution after traversing 22-mm length of 1-mm square fiber with perfect corners.



(c) Calculated intensity distribution after traversing 22-mm length of 1-mm square fiber with perfect corners.

Figure 3. Simulation of intensity distribution modification by square fiber.

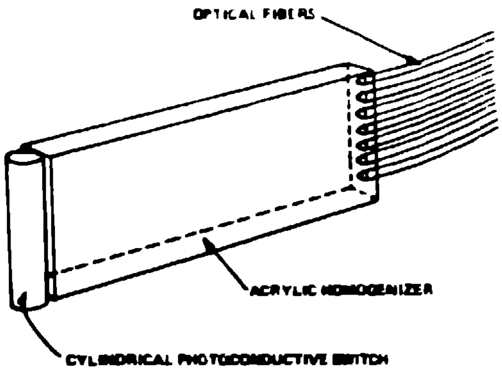


Figure 4. Illustration of cylindrical switch optical intensity homogenizer.

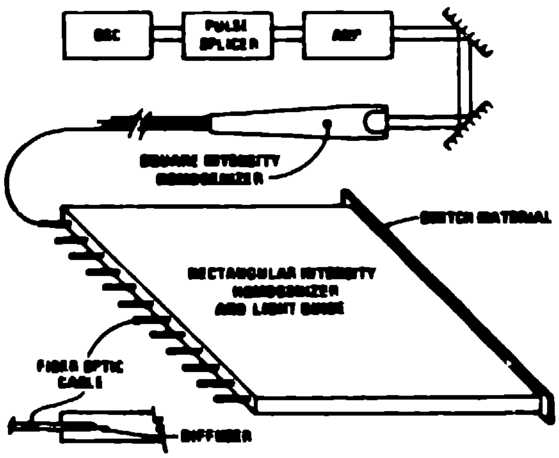


Figure 5. Illustration of low-inductance-strip PCPS optical intensity homogenizer.

shown in Figure 6. Figure 6a illustrates the intensity when the diode array is perpendicular to the length of the homogenizer at distances of 3.8 mm and 1.27 mm from the face. Figure 6b shows the intensity distribution from one end along the long side of the rectangular homogenizer. The photodiode array package limited the closest distance to the face of the homogenizer to about 1.27 mm. Note also in Figure 5 that a second homogenizer is used to equalize the optical intensity entering the fiber optic bundle. Because now the homogenizer has the largest mass when compared with the volume of switching material and is an insulator, it can be used as the basis for a modular switch(3).

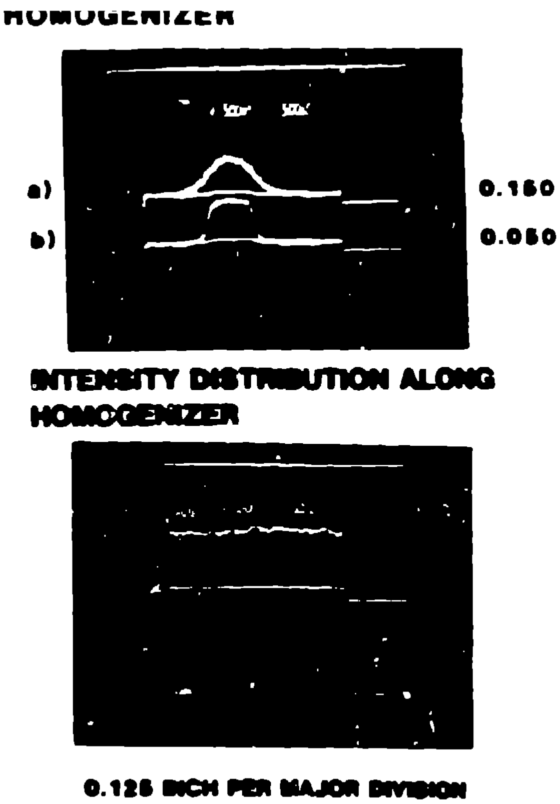


Figure 6. Measurement of optical intensity distribution at homogenizer output face.

PCPS Figure of Merit

The desired characteristics of a PCPS can be used to determine a qualitative figure of merit. First, a large "off" switch resistance is desired, requiring a large bulk resistivity ρ_b. Upon switching, a large absorption depth d_e is desired to increase the current per unit width as much as possible, and a large mobility μ is desired to reduce the "on" resistance after the carriers are optically generated. The carrier recombination time T_r should be large so that the optically produced carriers can be used to conduct a long-duration electrical pulse without increasing the switch resistance. These desired characteristics lead to a figure of merit for PCPSs(3):

$$F_m = \rho_b \, n_{p-max} \, d_e \, \mu \, e \, T_r \quad . \qquad (4)$$

where n_{p-max} is 10^{24} m^{-3} and e is the electron charge. The figure of merit for silicon is about 2, whereas that for GaAs is on the order of 0.001.

Contact and Surface Development

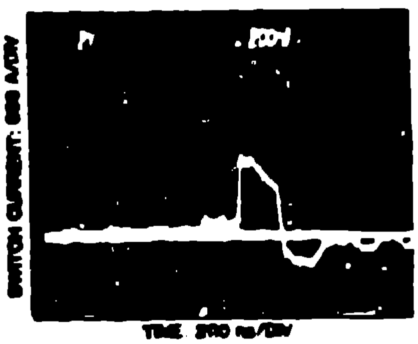
PCPS resistance is reduced to the conduction value by the uniform generation of electron-hole pairs between the switch electrodes at the carrier density required. The electric field is reduced from 100 kV/cm before illumination to about 1 kV/cm during conduction. The carriers move in the conduction electric field and are swept out opposite ends of the PCPS. The junction between the photoconductor and the metal conductor forms a Schottky barrier that impedes carrier reinjection and results in an effective carrier lifetime that is less than the bulk recombination time. This effect has been countered by fabricating heavily doped ohmic contacts at each end of the PCPS to reduce the thickness of the Schottky barrier and permit efficient tunneling. The large carrier density and the conduction electric field generate very large fields near the contact to promote carrier injection and the formation of an equilibrium electric field(3).

[illegible] easily overcome the Schottky barriers so that efficient carrier reinjection will occur.

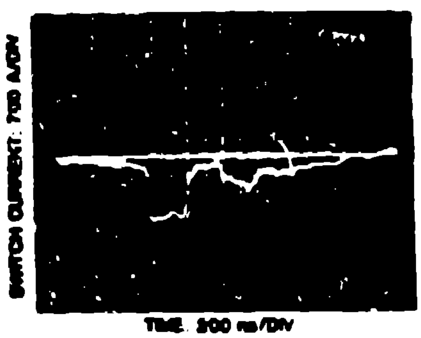
Carriers can be lost through recombination at the surface of the PCPS. Passivation of the photoconductor surface minimizes the surface states and reduces the probability of recombination at the surface. Photoconductor surface passivation has been pursued as a means of reducing surface flash- over, but it is also beneficial in increasing the effective carrier lifetime.

The current waveforms shown in Figure 7 illustrate the improvement in carrier lifetime brought about by either ohmic contact fabrication or surface passivation or both. Figure 7a illustrates the initial current waveform, initiated with a 20-ns laser pulse and terminated by the 200-ns pulse-forming line (coaxial cable section). Figure 7b illustrates an increase in effective carrier lifetime to about 10 µs as a result of both ohmic contact fabrication and surface passivation. Further experiments are being conducted to determine which fabrication process is responsible for the increase in carrier lifetime.

The elimination of surface flashover at electric fields up to 100 kV/cm is a major development effort. This is important because the optical energy required for switching scales with the square of the device length for a desired resistance. The required length of the PCPS is determined by the ratio of the maximum operational voltage to the electric field that the switch surface can support[1]. Therefore, PCPS operation at a larger electric field strength reduces the switch length and reduces the optical energy required. Previous experiments have operated routinely at an excessive level without surface flash-over. Recent experiments have evaluated PCPSs with extremely uniform SiO_2 passivation and with Si_3N_4 encapsulation. This surface fabrication system operates routinely up to 50 kV/cm and sometimes up to the 60-kV/cm level.



a) CURRENT WITHOUT CONTACT/SURFACE PREPARATION



b) CURRENT WITH CONTACT/SURFACE PREPARATION (INVERTED)

Figure 7. Current waveforms indicating increased carrier lifetime.

The voltage and current waveforms for a switch with the surface passivation and encapsulation are illustrated in Figure 8. The switch resistance at low voltages is about 10 kΩ; however, the switch current just before optical pulse arrival and at an applied voltage of about 160 kV is about 160 amperes, which indicates a resistance of about 1 kΩ. This unexpectedly large current is thought to be responsible for the surface flashover. Both recent experiments and previous experiments indicate a connection between the surface preparation and the initial current and the flashover voltage. Most recently, a specially fabricated sample failed through the bulk material without surface flashover at about 70 kV/cm. Current filamentation due to thermal runaway in the center of the device is presently thought to be responsible for the bulk material failure.

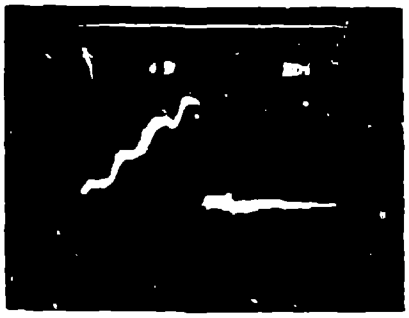
About 20 mJ of optical energy or an average peak optical power of 1 MW is delivered to the switch in a 20-ns pulse to produce the waveforms shown in Figure 1. The power delivered to the 25-Ω resistive load is about 200 MW during the 200-ns duration pulse so that the power gain is about 200, while the switched energy gain is about 2000. Switch resistance during conduction is about 0.8 Ω as determined from the switch voltage and current shown in Figure 8. The conduction resistance value is consistent with the optical energy deposited in the switch.

<u>Resonant Pulse Charge Limitations</u>

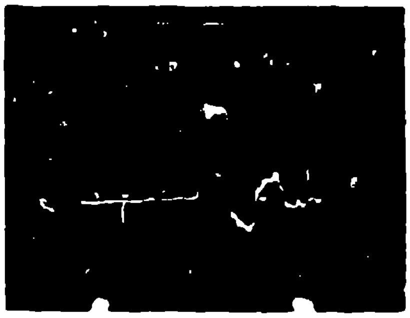
The bulk resistivity of a PCPS determines the current leakage before switching and also the rate at which thermal energy is dissipated in the switch. Because switch resistance decreases with increasing temperature due to the additional carriers generated by thermal action, the bulk resistivity determines the length of time that the switch can hold off a large voltage without conducting as a result of thermal runaway. If the switch is assumed to absorb all the energy resistively deposited during pulse charge and the carrier density is assumed to vary classically with temperature, the separable, iterative equation for the temperature of the switch material[7] is given by

$$\int \frac{e^{(B/(2T))}}{T^{3/2}}\, dT = \int \gamma\, \alpha^{1/2}\, V(t)^2\, dt \quad , \qquad (4)$$

where γ and α are constants related to the mass, the specific heat, and the effective mass of the electrons and holes in the photoconductor[7]. The principal material to be investigated is silicon with an intrinsic bulk resistivity of several hundred thousand ohm-cm. An intrinsic resistivity of 200 kΩ-cm corresponds to a room temperature carrier density of about 10^{8} cm^{-3}, but the actual resistivity readily available is about 2 kΩ-cm with an initial carrier density of about 10^{12} cm^{-3}. If the intrinsic values are used in solving Equation (4), then it should be possible to pulse charge a silicon switch 2.5 cm long with a 1-cm diameter to 250 kV in a resonant half-period of 100 µs. However, if the lower resistivity [illegible] is used, the switch can be [illegible] charged to the 250-kV level (100 kV/cm) in only 3. μs with a 10% decrease in resistance[7].



a) VOLTAGE ACROSS SWITCH (40 kV/DIV)



b) CURRENT (800 A/V)

Figure 8. 200 MW PCPS voltage and current waveforms.

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